CIMMYT

International Maize and Wheat Improvement Center

New Wheats

for a Secure, Sustainable Future

Timothy G. Reeves, Sanjaya Rajaram,
Maarten van Ginkel, Richard Trethowan,
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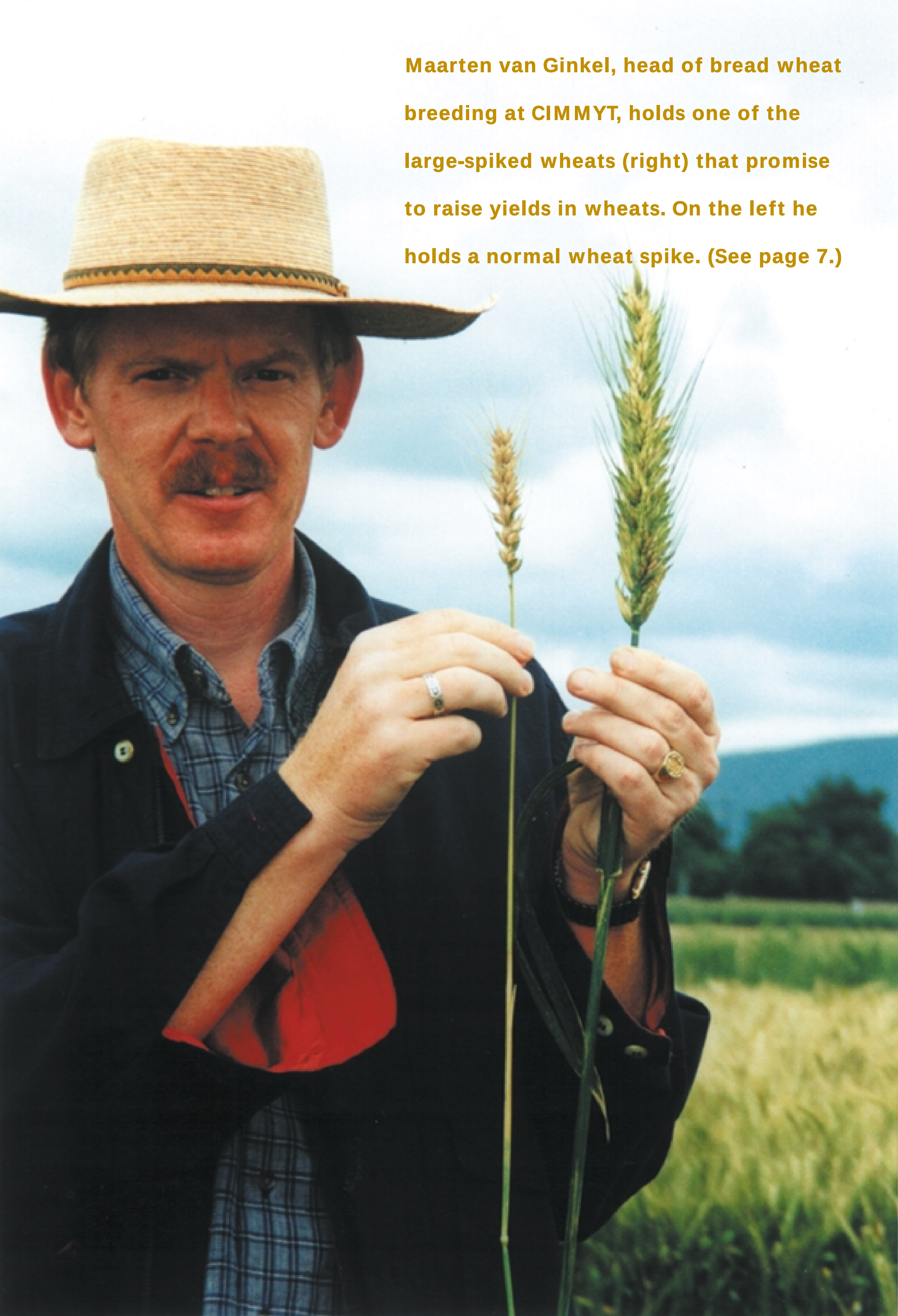

Maarten van Ginkel, head of bread wheat breeding at CIMMYT, holds one of the large-spiked wheats (right) that promise to raise yields in wheats. On the left he holds a normal wheat spike. (See page 7.)

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Abstract: This paper reviews strategies used by CIMMYT and its partners to develop sustainable wheat production systems for favored and marginal areas. These strategies aim to achieve an optimal combination of the best genotypes (G), in the right environments (E), under appropriate crop management (M), and appropriate to the needs of the people (P) who must implement and manage them. The first section of the paper presents new options for raising wheat yield potential and discusses research on disease and stress tolerance, which is aimed at protecting yield potential in farmers' fields (with special emphasis on drought tolerance). Next, advances in durum wheat yield potential are reviewed; these advances may prove particularly valuable in marginal environments. Other wheat research initiatives for marginal environments are described as well. This is followed by a review of the role of biotechnology in wheat improvement, research on wheat quality, and initiatives in crop and natural resource management research. The paper concludes with a summary of the latest data on the global impacts of wheat research and a discussion of trends that could affect whether and how this impact is maintained.

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Contents

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New Wheats for a Secure, Sustainable Future

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At the same time that we are witnessing a proliferation of agricultural innovations unlike any seen previously, hunger and poverty remain the defining conditions of life for hundreds of millions of people.

New agricultural knowledge and technologies are announced almost daily. The shifting alliances and the achievements of transnational seed-chemical-pharmaceutical companies are minutely analyzed in the media. It is easy to forget that this frenetic activity occurs in a sobering context—a world of persisting hunger.

Even a small number of facts are sufficient to demonstrate the gravity of the world food situation. More than 800 million people in developing countries—20% of the population—cannot be certain that they will get enough to eat, because they lack the resources to grow or purchase sufficient food. The downward spiral of hunger and poverty remains serious in many regions and countries. An estimated 1.3 billion people live in households earning US$ 1 per day or less per person. Asia has 73% of the world's poor people (World Bank 1997), and as we move into the new millenium South Asia will continue to be the home of half of the world's poor. Though Asia will have the highest absolute number of poor people, the number of poor people in Sub-Saharan Africa (which currently has 17% of the world's poor) will grow by 40% between 1990 and 2000, and the number of undernourished people will rise by 70% between 1988-90 and 2010 (World Bank 1997; Reeves, Pinstrup-Anderson, and Pandya-Lorch 1997).

Developing countries are projected to increase their demand for cereals by about 80% between 1999 and 2020 (Pinstrup-Andersen and Pandya-Lorch 1997). Rosegrant et al. (1997) report that over the next two decades global demand for wheat and maize could rise by 40% and 47%, respectively. By 2020, it is expected that 67% of the world's wheat consumption and 57% of the world's maize consumption will occur in developing countries.

Even if food crop productivity in developing countries remains at current levels, by 2020 developing countries will be importing 138 million tons of wheat and 62 million tons of maize every year. In these circumstances, how will we ensure food security for the poorest of the poor?

Agriculture: An Agent of Change

The role of more productive, profitable maize and wheat systems in fostering food security, generating local employment, raising local incomes, and thus alleviating poverty must not be underestimated. A recent report (UNDP 1997) emphasizes that agricultural research is the central means of achieving those goals: "About three-quarters of the world's poorest people live in rural areas, dependent on agricultural activities for their livelihoods. For these people, pro-poor growth means raising agricultural productivity, efficiency, and incomes." The report points out why agriculture can succeed where other initiatives might fail: "Raising the productivity of small-scale agriculture does more than benefit farmers. It also creates employment on the farm and off—and reduces food prices. The poor benefit most, because about 70% of their consumption is food, mostly staples, and regular supplies and stable prices can greatly reduce the vulnerability of the poor. Strong support to small-scale agriculture was at the core of the most successful cases of poverty reduction—such as China in 1978-85, Malaysia since 1971, and India in the early 1980s."

In these circumstances, the challenges for research—and the opportunities to alleviate much human suffering—are clear. We will have to develop the innovations that make it possible for people to benefit from more efficient, low-cost systems for food production. These systems must function without mining the natural resources on which agriculture depends. They are needed urgently in favored as well as less favored agricultural areas.

In this paper, we review strategies used by the International Maize and Wheat Improvement Center (CIMMYT) and its partners to develop sustainable wheat[1] production systems for favored and marginal areas. These strategies aim to achieve an optimal combination of the best genotypes (G), in the right environments (E), under appropriate crop management (M), and appropriate to the needs of the people (P) who must implement and manage them (Reeves 1998, 1999). Each variable in this GxExMxP "sustainability equation" is addressed in the sections that follow. After further defining what we mean by "sustainable technology," we:

- Review new options for raising wheat yield potential.
- Discuss research on disease and stress tolerance, which is aimed at protecting yield potential in farmers' fields. We give special emphasis to drought tolerance.
- Describe advances in durum wheat yield potential which may prove particularly valuable in marginal environments.

1 In this paper we focus on strategies related to wheat, although CIMMYT's research mandate encompasses maize as well. We also give greater attention to wheat genetic improvement than to crop and natural resource management research, but readers should be advised that CIMMYT engages in a great deal of crop and resource management research, for wheat as well as maize. For a general overview, see our annual report, *CIMMYT in 1998-99: Science to Sustain People and the Environment.*

- Provide an overview of other wheat research initiatives for marginal environments.
- Review the role of biotechnology in wheat improvement.
- Describe recent research on wheat quality. For many poor farmers, an increase in wheat quality means a corresponding increase in income.
- Briefly review recent initiatives in crop and natural resource management research in wheat.

We conclude by summarizing the latest data on the global impacts of our wheat research and by discussing trends that could affect whether and how this impact is maintained into the future.

Prerequisites for Sustainable Agriculture

To be sustainable, farming systems must be biologically sensible, economically viable, environmentally sound, socially acceptable, and politically supportable (Reeves 1998, 1999):

- Sustainable farming systems must be biologically sensible. For example, the choice of crop(s), their management, and the level of intensification must be consistent with the biophysical realities of the farming system.
- Sustainable farming systems must be economically viable at the farm and national levels. Poor farmers cannot invest in systems that will not produce reasonable yields and (even better) cash income, now and in the future. At the national level, the reality in most developing countries is that economic well-being and development are almost invariably based on productive and profitable agriculture, the "engine room" of subsequent industrialization.
- Sustainable farming systems must be environmentally sound. Economic success in agriculture cannot come at the expense of our soils, air, water, landscapes, and indigenous flora and fauna.
- Sustainable farming systems must be socially acceptable. They must be appropriate to the people who, relying on their own meager resources, are responsible for implementing and managing them. The need for socially acceptable systems implies the need for a better understanding of farmer and community needs and values, as well as better targeting of technology to meet local conditions.
- Finally, sustainable farming systems must be politically supportable. Political support depends largely on successfully meeting the first three requirements of sustainability. If economic growth is catalyzed by agriculture within an environmentally sound, socially acceptable framework, politicians will continue to view agriculture as justifying support.

All of these components combine to form the whole: sustainable agriculture. If one is neglected, it can seriously reduce the rate and extent of progress towards sustainability and food security.

Breeding Wheats for Lasting Food Security

CIMMYT's wheat breeding methodology is tailored to develop widely adapted, disease resistant germplasm with high and stable yield across a wide range of environments—favorable as well as marginal. To focus this work, we have grouped wheat production areas in developing countries into 12 "mega-environments." A mega-environment is a broad but not necessarily contiguous geographical area, usually international and frequently transcontinental. Mega-environments are defined in terms of the type of wheat cultivated (spring, facultative, or winter wheat), the amount of water available to the crop, temperature regime, mineral toxicity in the soil, and the major diseases and pests that limit food production.

CIMMYT wheat breeders, through collaboration with national wheat research programs and genebanks, scour the world for new and different sources of yield potential and other traits of interest. We give the utmost attention to genetic diversity within CIMMYT germplasm to minimize the risk of genetic vulnerability, since our breeding materials are used in research programs worldwide, and the numerous varieties developed from those breeding materials are grown by hundreds of millions of farmers. We also believe that the use of genetically diverse material is mandatory for future increases in yield potential and yield stability. At CIMMYT, parental groups of lines for crossing in any year consist of 500-800 lines. Twice a year around 30% of parental stocks are replaced with outstanding introductions. In addition, commercial cultivars from national agricultural research systems (NARSs) and non-conventional sources (e.g., durum wheat and alien species) are used to incorporate desired traits by recombination or translocation. The introductions are mostly used as the female parent to preserve cytoplasmic diversity.

Options for Increasing Yield Potential

Like most wheat improvement programs, the CIMMYT wheat improvement program has many reasons for seeking to raise—and protect—genetic yield potential. High yield potential, assessed in breeders' trials, is positively associated with superior crop performance in farmers' fields, even in stressed environments. Another consideration is that most farmers readily adopt and share improved wheat seed, even in areas where problems with infrastructure and lack of farmer support services frustrate the adoption of other agricultural inputs and practices.

Those may be regarded as the "humanitarian" reasons for seeking higher yields, but it is important to remember that there are also compelling environmental reasons to break yield barriers. We must be realistic about changing land use patterns and their implications for agriculture. There is limited scope to open new land for crop production, and there is an even more urgent need to protect land (in particular, marginal land) from inappropriate uses. In recent decades developing countries have fortunately relied more on increased yields than on an expansion of cropped area to feed their populations. Between 1961 and 1990, yield increases accounted for 92% of the additional cereal production in the developing world (Reeves, Pinstrup-Anderson, and Pandya-Lorch 1997). When farmers in stable, high production environments obtain better yields, the need to intensify production in fragile agricultural systems is reduced, offering a much more sustainable approach to meeting long-term demand for cereal production in developing countries.[2] Because higher yielding lines are frequently bred to use inputs such as nutrients and water more efficiently, higher yields are not obtained at a higher cost to the environment. As our CIMMYT colleague, Nobel Laureate Norman Borlaug, has said, “The only way for agriculture to keep pace with population and alleviate world hunger is to increase the intensity of production in those ecosystems that lend themselves to sustainable intensification, while decreasing intensity of production in the more fragile ecologies” (Borlaug and Dowswell 1997).

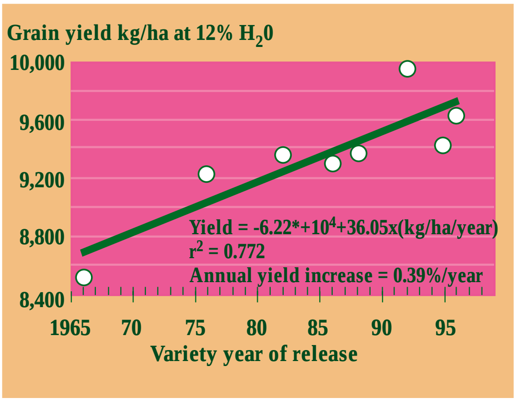

Figure 1. Grain yield trend for semidwarf bread wheat lines developed at CIMMYT since 1966, under conventional planting, average for 1997, 1998, and 1999 crop cycles at CIANO, Cd. Obregón, Mexico.
Source: K.D. Sayre, CIMMYT.

The selection of segregating populations and consequent yield testing of advanced lines is paramount for identifying high yielding, input responsive wheat genotypes. The increase in yield potential of CIMMYT cultivars developed since the 1960s is shown in Figure 1 (K. Sayre, pers. comm.). The data do not indicate that we are approaching a yield plateau, and the performance of recently released lines such as Attila and Baviacora, and of *Lr19*-derived Veery, indicates that yield potential has been further enhanced.

With yield, a complex trait still not well understood genetically or physiologically, the use of proven, high yielding sources, as well as genetically diverse germplasm, will continue to be paramount for increasing yield potential. Genetic diversity and the opportunity for its recombination through crossing will be important to break undesired linkages and increase the frequency

2 For example, if India were suddenly required to produce its current wheat harvest using the technologies of 30 years ago, Indian farmers would have to bring more than 40 million hectares of additional land into production. The wheat varieties developed in the past three decades were instrumental in preventing damage to areas that are not well suited to agriculture.

of desirable alleles. Future breakthroughs in yield potential are likely to come from such genetically diverse crosses. Examples are given below, along with a description of other efforts to raise both spring and winter wheat yield potential.

Gene Pools of Winter and Spring Hexaploid Wheats

The variability currently available among spring and winter hexaploid wheats is still extensive. New high yielding sources from within the CIMMYT Bread Wheat Program and from around the world are identified and intercrossed. For example, high yielding spring wheat lines from South Asia and China are regularly intercrossed with the highest yielding lines identified in Mexico, followed by selection for types superior to either parent, carrying all desirable genes. Likewise elite winter wheats are intercrossed. Considerable progress can still be made in this way as yield is controlled by many genes and the optimal combinations of these genes for any particular environment may not yet have been realized.

Introgressing Spring and Winter Wheat Gene Pools

By introgressing genetic variability from winter wheats, breeders have considerably augmented the yield potential of spring wheats. The Veery wheats, developed from crosses of CIMMYT spring wheats and Russian winter wheat, represented a quantum leap in spring wheat yield and wide adaptation during the 1970s and 1980s (CIMMYT 1986) (their contribution to drought tolerance is discussed later). More recently, the spring bread wheat Attila, developed from crosses with western European and US winter wheats, has rapidly gained ground on the Indian subcontinent. New evidence indicates that yield potential in winter wheat may also benefit from crosses with high yielding spring wheats.

Chinese Wheats: A Wellspring of Diversity

Before the mid-1980s, only a limited amount of wheat germplasm from outside China was available to Chinese breeders. Since the mid-1980s, CIMMYT and Chinese scientists have worked together to benefit from the diversity in each others' wheat germplasm. More than 100 Chinese varieties contain CIMMYT germplasm, and up to 20% of new CIMMYT spring wheats have Chinese wheats in their pedigrees. Apart from its resistance to biotic pests such as scab and Karnal bunt, modern Chinese germplasm offers new alternatives for raising the yield potential of wheat; yields of elite Chinese wheats in China can exceed 10 t/ha.

Hybrid Wheats

The expression of heterosis for yield in wheat can be high. Although it has been well documented, heterosis has not been exploited commercially to any great extent. Hybrids offer the unique opportunity of combining different gene pools in the production of the F1 hybrid. Because heterosis is, to some extent, a function of genetic distance, CIMMYT is well positioned to exploit this need for genetic diversity. During the past three years, CIMMYT hybrids have produced yields that are 15-20% higher than those of commercially grown cultivars in Mexico, and levels of heterosis of a similar maximum size have been reported. The difficulty of producing F1 seed in a cost-effective way remains the greatest limitation to the exploitation of such hybrids, but CIMMYT breeders expect to resolve this issue by introgressing outcrossing traits.

Landraces

Many high yielding CIMMYT wheats have a considerable number of landraces in their pedigrees. A coefficient of parentage analysis reveals that on average CIMMYT advanced lines contain as many as 50 landraces in their genetic history. Breeding programs have still not exploited all of the yield-controlling genes available in landraces. Landraces may also provide novel sources of adaptation, which will allow breeders to select more stable, high yielding lines. As yields increase, consumer preferences will also turn to increased quality and taste. Here, locally preferred landraces can play a very new and exciting role.

Improved Plant Ideotype

CIMMYT breeders are using increased knowledge of the physiological bases of yield to define a range of optimal wheat plant ideotypes. We are examining plants with large spikes, which contain many grains per spikelet (see photo, inside front cover). The optimization of source-sink relationships is also being examined with a view to obtaining a better balance of grain-filling characters. The hexaploid wheat and other gene pools are being searched for examples of extreme expression of these characters. We believe advances of yield potential on the order of at least 20% in optimum conditions can still be realized by fine-tuning the source-sink relationships in wheat.

Phenological Traits

By manipulating photoperiod and vernalization genes, we are attempting to tailor genotypes to specific environments. Photoperiod and vernalization genes optimize the timing and duration of flowering and grain-filling, thereby influencing the wheat plant's eventual yield. New and different sources of these genes are being exploited through the use of high-latitude germplasm from Central Asia and Canada.

Physiological Traits

A strong body of evidence now indicates that physiological traits may complement early-generation phenotypic selection in wheat. Genetic progress in increasing yield potential is closely associated with increased photosynthetic activity (Rees et al. 1993). Photosynthetic activity as well as yield potential have increased over the past 30 years by some 25%. These findings may have major implications for CIMMYT's future selection strategy, since there is evidence that wheat genotypes with higher photosynthesis rates have lower canopy temperatures, a characteristic that can be measured easily, quickly, and cheaply. Canopy temperature depression (CTD) is the cooling effect exhibited by a leaf as transpiration occurs. Canopy temperature depression and stomatal conductance, measured on sunny days during grain filling, have shown a strong association with yields of semidwarf wheats grown under irrigation, in both temperate (Fischer et al. 1998) and subtropical environments (Reynolds et al. 1994). In addition, CTD measured on large numbers of advanced breeding lines in irrigated yield trials was a powerful predictor of performance, not only at the selection site but also for yield averaged across 15 international sites. Canopy temperature depression has been shown to be associated with yield differences between homozygous lines in warm environments, indicating a potential for genetic yield gains under conditions of heat in response to selection for CTD (Reynolds at al. 1998). Breeders have found CTD to be highly correlated with yield under heat conditions among elite lines (van Ginkel and Trethowan, unpublished), and the technique may be particularly useful for more efficiently selecting wheat genotypes adapted to environments where heat is a production constraint.

Synthetic Wheats: Delivering Diversity to Plant Breeders

Synthetic wheats are the result of a cross between two relatives of putative progenitors of wheat, *Triticum turgidum* and *T. tauschii*, with subsequent chromosome doubling. Historically (10,000 to 8,000 years ago), this cross has probably occurred on only a few occasions. As a result, the genetic resources of these two species have been sampled in only a limited way in the development of bread wheat. CIMMYT holds a large number of *T. tauschii* accessions from which many new synthetic hexaploid wheats have been made (about 650 to date). These synthetics possess a range of positive traits, including resistance to such diseases as Karnal bunt, fusarium head scab, and helminthosporium leaf blotch, and tolerance to heat, drought, waterlogging, and late frost at flowering. They are spring types that are highly crossable to advanced bread wheats, which means that they may be used easily in breeding programs. Through this approach, CIMMYT breeders have not only been able to take advantage of the new variation from *T. tauschii*, but have also found a new way to introgress traits from elite durum wheats into bread wheat. Synthetics or their derivatives may also prove useful in the production of hybrid wheat and the improvement of bread wheat quality.

Alien Substitutions and Translocations

The 1B/1R translocation (discussed also in the section on drought tolerance) led to a revolution in the broad adaptation of wheat. This translocation from rye increased wheat biomass, harvest index, and—especially—wide adaptation, which spurred improvements in wheat yield in most spring wheat environments. More recently, a translocated segment from *Agropyron* sp. containing the leaf rust resistance gene *Lr19* has been linked with a 5-10% increase in yield in adapted backgrounds. Other alien sources of higher yield are also currently under evaluation.

Protecting Yield Potential: The Role of Resistance to Pathogens and Pests

Over the past few decades, the gains from breeding for disease resistance are likely to have been at least as important as the gains from breeding for increased yield potential (Byerlee and Moya 1993). A recent survey of wheat breeders in developing countries indicated that among the types of materials used in crossing (including the breeder's own advanced lines, advanced lines obtained from other countries, wild relatives, and landraces), materials from CIMMYT international nurseries are the most frequently crossed in pursuit of disease resistance goals (Rejesus, van Ginkel, and Smale 1996).

CIMMYT's global effort to breed wheats with diverse and durable resistance will protect global food security by reducing the incidence of disease epidemics. It will also protect the environment and farmers' incomes, by reducing dependence on pesticides for disease and pest control. In CIMMYT's target mega-environments, important fungal diseases of wheat caused by obligate parasites include the rusts (one or more of which are the most economically important diseases in most wheat production environments), powdery mildew, and the bunts and smuts. Widespread diseases caused by facultative fungal parasites include septoria tritici blotch, septoria nodorum blotch, spot blotch, tan spot, head scab, and a suite of root rots.

The obligate parasites are highly specialized, and significant variation exists in the pathogen population for virulence to specific resistance genes. The evolution of new virulence (races) through migration, mutation, and recombination of existing virulences and their selection is more frequent in rust and powdery mildew fungi. For this reason, these diseases have required constant vigilance and attention from breeders. Physiological races are also known to occur for most bunts and smuts, although evolution and selection of new races is less frequent. Because most bunts and smuts are easily controlled by chemical seed treatment, little effort is currently placed on breeding for resistance, except for resistance to Karnal bunt. Successful changes in pathogen races are even less frequent in the facultative parasites mentioned earlier.

Since wheat cultivars derived from CIMMYT germplasm are grown over a large area and are exposed to a variety of pathogens under conditions that may favor disease development, our strategy has been to utilize resistance sources that are as diverse as possible and have shown durability. Genetic diversity and durability of resistance against diseases caused by pathogens such as the rust pathogens are vital for long-term food security. Resistances caused by race-specific genes become ineffective in a short time (in five years on average at the global level and in three years for leaf rust, *Puccinia recondita*, in Mexico). In contrast, cultivars with durable resistance have shown stable resistance for over 50 years at the global level. Consider the resistance to stem rust (*P. graminis*). McFadden in the US transferred the *Sr2* gene complex from a tetraploid emmer wheat to hexaploid bread wheat in the 1920s (McFadden 1930). Borlaug in Mexico used this source of resistance in his breeding program in the 1940s, and since then this gene, in concert with several known and unknown major and minor genes, has formed the basis of durable resistance to stem rust in CIMMYT wheat germplasm.

Following the lesson learnt from stem rust research, CIMMYT's wheat breeding in the last three decades has focused on utilizing diverse sources of slow rusting resistance to *P. recondita* and yellow rust (*P. striiformis*). Genetic analyses of durable resistance indicate that effective disease control can be achieved by combining from three to five minor, slow rusting genes in a single cultivar. Such resistance is expected to provide sufficient protection to farmers' crop against all biotypes over a long period. Currently we are also attempting to identify molecular markers for each of the slow rusting genes present in CIMMYT wheats. If this strategy is successful, breeding programs will be able to incorporate known combinations of minor genes, develop a global strategy for their deployment, and at the same time enhance genetic diversity in farmers' fields.

Recent analysis of trials conducted in northwestern Mexico confirms that progress in protecting yield potential through genetic resistance to leaf rust is about three times as great as advances in yield potential itself (R.P. Singh and K.D. Sayre, pers. comm.). The economic benefits of CIMMYT's strategy of incorporating non-specific, durable resistance to leaf rust into modern bread wheats have been estimated using data on resistance genes identified in cultivars, trial data, and area sown to cultivars in northwestern Mexico. Even under the most conservative scenario, the gross benefits generated in this region on about 120,000 ha of wheat from 1970 to 1990 were US$ 17 million (in 1994 real terms) (Smale et al. 1998). At the global level, where a considerable area is sown to cultivars carrying non-specific resistance, the benefits must be correspondingly large.

Resistance to the diseases caused by facultative parasites, such as *Septoria tritici* and *Fusarium graminearum*, also involves genes that have additive effects. Tremendous progress has been made at CIMMYT in developing semidwarf wheats that have adequate resistance to *Septoria tritici*. Sources contributing to resistance include wheats from France, Brazil, China, and Russia. More recently we have identified synthetic wheats (*T. turgidum* x *T. tauschii*) possessing good resistance to septoria tritici blotch. This new genetic diversity is currently being transferred to CIMMYT wheats.

Moving beyond Marginal Yields in Marginal Environments

Limited water availability is probably the most common stress that affects farmers in marginal environments, but they also have to contend with factors such as diseases, acid soils, extreme cold and heat, waterlogging, and mineral deficiencies and toxicities. A region is defined as marginal when wheat production drops to 70% of optimal yield levels, as in, for example, the highland areas from Turkey to Afghanistan, the dryland areas of West Asia and North Africa (WANA), much of Ethiopia, and the dryland areas of central and southern India (Table 1).[3]

Our discussion of CIMMYT's research directed at marginal areas begins with a review of the methods used in breeding drought tolerant wheats. Next, we describe achievements in durum wheat breeding, given the considerable amount of durum wheat grown in marginal areas. We conclude with an overview of specific research initiatives in regions where marginal environments present a series of challenges to wheat production. As the following sections indicate, CIMMYT researchers and their collaborators are implementing a combination of strategies to ensure that farmers in marginal areas are no longer destined to obtain marginal yields.

3 Note that, although improved varieties have a role to play in these areas, considerable gains will also result from improved crop and resource management, especially measures to conserve and utilize moisture more efficiently in rainfed areas. Some of these practices are discussed later in this publication.

Table 1. Portions of wheat producing regions of the world that are defined as marginal

Region	Total wheat area (000 ha)	Percent marginal
West Asia / North Africa	28,300	65
Central Asia and the Caucasus	15,000	80
South Asia (Subcontinent)	34,500	35
East Asia (including China)	30,100	13
Eastern Africa	1,500	27
Southern Africa	1,300	91
Southern Cone of South America	7,400	60
Andean Region of South America	300	18
Mexico / Central America	900	43
Total	**119,300**	**45**

Breeding for Drought Tolerance

The annual gain in genetic yield potential in drought environments is only about half (0.3-0.5%) of that obtained in irrigated, optimum conditions. Many investigators have attempted to produce wheat adapted to semiarid environments but with limited success. The CIMMYT Wheat Program follows a system of breeding for drought tolerance in which yield responsiveness is combined with adaptation to drought conditions. Because most semiarid environments differ significantly in annual precipitation distribution, and because water availability also differs across years in these environments, it is prudent to construct a genetic system in which plant responsiveness provides a bonus whenever higher rainfall improves the production environment. With such a system, improved moisture is immediately translated into greater yield gains for farmers.

Why do we believe that this can be done? One compelling piece of evidence comes in the form of Veery S, which combines high yield performance in favorable environments and adaptation to drought in more marginal areas. When Veery S was tested in 73 environments in the early 1980s, its performance differed from that of other high yielding varieties. It yielded better than other cultivars not only in high yielding environments but also under reduced irrigation (Table 2). What made this line different was that it carried the 1B/1R translocation from rye. By 1990, 63% of the dryland wheat area in developing countries was sown to semidwarf wheats (Byerlee and Moya 1993). Many of these wheats possessed the 1B/1R translocation, which had been incorporated into hundreds of genetically different backgrounds and made available to breeders throughout the world.

We have conducted several experiments to compare the performance of the newest and most widely adapted wheat germplasm to the performance of commercial cultivars from countries in three marginal, low rainfall mega-environments, under conditions simulating those environments (Calhoun et al. 1994; van Ginkel et al. 1998; Tables 3 and 4). The most widely adapted CIMMYT lines yielded better than the commercial cultivars in all of the simulated environments. Recent adoption of

Table 2. Effect of the 1BL/1RS translocation on yield characteristics of 28 random F2-derived F6 lines from the cross Nacozari/Seri 82 under reduced irrigation

Characteristic	1BL/1RS	1B	Mean difference
Grain yield (kg/ha)	4,945	4,743	202 *
Above-ground biomass at maturity (t/ha)	12,600	12,100	500 *
Grains/m^2	14,074	13,922	152 NS
Grains/spike	43.5	40.6	2.9 *
1,000-grain weight (g)	37.1	36.5	0.5 *

Source: Villareal et al. (1995).
Note: NS = not significant; * = significant at the 0.05 level.

Table 3. Wheat genotypes representing adaptation to different moisture environments

Mega-environment (ME)		Genotype
ME1	(Irrigated environment)	Super Kauz, Pavon 76, Genaro 81, Opata 85
ME4A	(Mediterranean Region)	Almansor, Nesser, Sitta, Siete Cerros
ME4B	(Southern Cone, S. America)	Cruz Alta, Prointa Don Alberto, LAP1376, PSN/BOW CM69560
ME4C	(South Asian Subcontinent)	C306, Sonalika, Punjab 81, Barani

Source: Calhoun et al. (1994).

Table 4. Grain yields (kg/ha) of selected wheat genotypes grouped by adaptation and tested under moisture regimes in the Yaqui Valley, Mexico, 1989/90 and 1990/91

Adaptation group		Full irrigation[a]	Late drought[b]	Early drought[c]	Residual moisture[d]
ME1	(Irrigated environment)	6,636 a	4,198 a	4,576 a	3,032 a
ME4A	(Mediterranean Region)	6,342 b	3,990 ab	4,390 b	3,032 a
ME4B	(Southern Cone, S. America)	5,028 c	3,148 bc	4,224 b	2,359 c
ME4C	(South Asian Subcontinent)	4,778 c	3,245 bc	3,657 c	2,704 b

Source: Calhoun et al. (1994).
Note: Means in the same column followed by the same letter are not significantly different at P=0.05.
a Received 5 irrigations.
b Received 2 irrigations early, before heading.
c Received 1 irrigation for germination and 2 post-heading.
d Received 1 irrigation for germination only.

CIMMYT germplasm in those environments supports the model of combining input efficiency and input responsiveness.

Another piece of evidence is Nesser, an advanced line with superior performance in drought conditions. Nesser was bred at CIMMYT-Mexico and identified by the CIMMYT Mediterranean program located at the International Center for Agricultural Research in the Dry Areas (ICARDA) in Syria. The cross combines the high yielding CIMMYT variety Jupateco 75 and the drought tolerant Australian variety W3918A. The performance of Nesser in the dryland environments of WANA has been widely publicized (ICARDA 1993), and the line is considered to represent a uniquely drought-tolerant genotype. This line was selected at CIMMYT/Mexico under favorable conditions, and it carries a combination of input efficiency and high yield responsiveness. In the absence of rust, its performance is quite similar to that of Veery S.

A breeding scheme to achieve the combination of yield responsiveness and drought tolerance in wheat is presented in Table 5. This method is supported by research on wheat as well as other crops, in which testing and selecting in a range of environments, including well-irrigated ones, has identified superior genotypes for stressed conditions (see, for example, Ehdaie, Waines, and Hall 1988; Duvick 1990, 1992; Bramel-Cox et al. 1991; Uddin, Carver, and Clutter 1992; Zavala-Garcia et al. 1992; and Cooper, Byth, and Woodruff 1994). The approach results in the selection of germplasm that is adopted by farmers because it translates improved environmental conditions into yield gains. The traditional methodology of selecting only under drought conditions and narrowly relying on landrace genotypes does not move yield levels significantly beyond those usually obtained, and it does not provide the farmer with a bonus in years when rainfall is higher.

Table 5. Methodology for breeding drought-tolerant wheat that is also responsive to favorable environmental conditions

Generation	Activity
F1	Crosses involving widely adapted germplasm, representing yield potential, yield stability, and input responsiveness, with lines carrying proven drought tolerance in the setting of the respective drought mega-environments (ME4A, ME4B, or ME4C), and input (water) use efficiency. Winter wheat and synthetics are emphasized.
F2	Individual plants are raised under irrigated and optimally fertilized conditions, and inoculated with a wide spectrum of rust virulence. Only robust and horizontally resistant plants are selected. These plants may represent adaptation and responsiveness to favorable environmental conditions.
F3	The selected F2 plants are evaluated as F3s in a modified pedigree/bulk breeding system (Rajaram and van Ginkel 1995) under rainfed conditions or very low water availability. The selection is based on such criteria as spike density, biomass/vigor, and grains/m^2, among others (van Ginkel et al. 1998). This index helps identify lines that may adapt to conditions in which water is limited (that is, lines that are input efficient).
F4	Selected lines from F3 are further evaluated under optimum conditions, as for the F2.
F5	As F3.
F6	As F4.
F7, F8	Simultaneous evaluations under low and intermediate (representing the higher rainfall years in marginal drought environments) water regimes. Selection of those lines showing outstanding performance under both conditions. Further evaluation in international environments is carried out for verification.

Higher Yielding Durum Wheats

Although durum wheat is not cultivated as widely as bread wheat, it occupies a special niche in the developing world. Durum wheat is generally sown in marginal environments subject to great climatic fluctuations during the growing season. The durum crop may experience heat and drought at different times during its growth cycle. Most of the developing world durum area is concentrated in the countries of WANA, but durum is also grown in central and south India,[4] Ethiopia, Mexico, Argentina, Peru, Kazakhstan, Azerbaijan, and Ukraine. Often the crop is grown by poor people who rely on it for a high proportion of calories in the diet or for income—as durum in some areas fetches a premium in the local market.

Short-cycle, semidwarf durum wheat varieties recently tested in northwestern Mexico produced a remarkable 89 kg of grain per hectare per day, for a final tally of 11.7 t/ha at harvest (W. Pfeiffer, pers. comm.). This

4 In parts of India, durum production is relegated to the hottest and driest environments.

is an increase of more than 20% over the previous generation of durum wheats. Generally average yields of durum wheat in farmers' fields in northwestern Mexico are 6 t / ha, and the world average is 2-3 t / ha. If these recently tested wheats retain some of their yield advantage in marginal conditions, they may prove to be a valuable asset for breeding programs.

Regional Research on Wheat for Marginal Environments

West Asia and North Africa. About one-third of the area planted to wheat in the developing world is located in marginal environments plagued by drought and soil problems. These problems are frequently exacerbated by a lack of infrastructure and farmer support services. Most of the world's drought-prone wheat area is concentrated in the WANA region (Table 1). Wheat is the principal food source for people in WANA, who on average consume more than 145 kg / cap / yr, one of the highest levels of per capita consumption in the world.

CIMMYT efforts aimed at improving wheat production in WANA are conducted in conjunction with ICARDA. The CIMMYT / ICARDA Joint Dryland Wheat Program for West Asia and North Africa seeks to increase wheat productivity by developing spring bread and durum wheats that are better adapted to the WANA region. Wheats developed or identified by the program are widely adapted and possess enhanced disease and insect resistance, as well as better tolerance to the prevalent abiotic stresses. This is why our partners in the region increasingly select them for use in their own breeding programs. Farmer adoption of CIMMYT- and CIMMYT / ICARDA-derived varieties in WANA continues to increase, with more than 90 wheat varieties released in 21 countries in the region over the past 10 years.

The Turkey / CIMMYT / ICARDA International Winter Wheat Improvement Program (IWWIP) based in Ankara, Turkey, came into existence 11 years ago with the purpose of generating winter wheats for developing countries, particularly in the WANA region. Over the past two years, IWWIP has expanded its collaboration with winter wheat programs in the developing world. New research partnerships with colleagues from Central Asia and the Caucasus have greatly increased the number of cooperators.

The program is devoting particular attention to improving resistance to yellow rust, which is the most serious winter wheat disease in WANA. It conducts trials using artificial inoculation in Ankara, Konya, and Eskisehir (Turkey), Aleppo (Syria), and Iran. It is also conducting research on micronutrients aimed at identifying zinc-efficient wheats to be used in crosses and alien materials that may be potential sources of zinc efficiency. At present, rye and triticale seem to be the best sources, but other alien species are also being tested at Turkey's Çukurova University.

Central Asia and the Caucasus. The republics of Central Asia and the Caucasus are relatively diverse in climate, agricultural production, and population. What these eight countries (Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tadjikistan, Turkmenistan, and Uzbekistan) have in common is that they are all in transition from being centrally planned economies to becoming market-oriented ones. Nearly 15 million hectares are planted to wheat in the region, but with the exception of Kazakhstan, all countries have to import wheat to satisfy domestic demand. A major objective of their governments is to become self-sufficient in wheat.

In 1992, after the political situation changed, CIMMYT re-established contacts with research programs in the region. In 1998, CIMMYT was mandated by the CGIAR to address the needs for wheat germplasm in this region. Breeders and research administrators from the region have visited IWWIP in Ankara or CIMMYT in Mexico, and CIMMYT scientists have visited several of the newly independent nations. In 1998 CIMMYT opened a regional office in Kazakhstan. There is now active exchange of germplasm and information. In the future, CIMMYT will initiate shuttle breeding programs with the region. A joint CIMMYT/Kazakhstan breeding program to combine quality, drought tolerance, and disease resistance in high latitude spring wheat is in the planning stages. If successful, it would contribute to the food security not only of Kazakhstan, but of the whole region.

Eastern Africa. Now in its fourth phase, the CIMMYT/Canadian International Development Agency Eastern Africa Cereals Program (EACP) has as its main objective to increase maize and wheat production and productivity in eastern Africa. During its third phase, the wheat component of the program focused heavily on developing sustainable production systems for the major wheat growing environments in the region and on strengthening national program commitment and capacity for long-term experimentation. During 1993-96, Kenya, Ethiopia, and Uganda released 13 CIMMYT-related bread wheat and durum wheat varieties. Studies conducted by the EACP in collaboration with Ethiopia and Kenya found that reduced or zero tillage produced either the same or better yields than conventional tillage systems. The EACP also developed agronomic recommendations to improve yields and nitrogen use efficiency in areas that experience waterlogging problems. An encouraging fact brought to light in a recent report by the EACP is that several decades of breeding durum and bread wheats from CIMMYT semidwarf wheats in Ethiopia have resulted in annual increases of 1.5-2.0% in yield potential based on rainfed experiments.

Improvements in Wheat Quality

Often wheat quality is perceived to be important only to large-scale farmers dedicated to commercial production. In fact, traits related to quality in wheat are even more important for many poor farmers, whose incomes may increase if they can produce wheat that receives a price premium for its quality characteristics.

Several studies have concluded that wild diploid species carrying A- and D-genomes have greater allelic variation than cultivated wheat for gene loci controlling glutenin subunits (Waines and Payne 1987; Lagudah and Halloran

1988; Ciaffi et al. 1992; Lafiandra, Ciaffi, and Benedetelli 1993; William, Peña, and Mujeeb-Kazi et al. 1993). These alien genes offer a potential means of expanding the number of allelic variants controlling proteins with desirable quality effects in wheat. Several of the synthetic hexaploids developed from accessions of diploid Triticeae species (*T. tauschii*, *T. boeoticum*, *T. monococcum*, and *T. urartu*) and durum wheat have been examined in relation to grain characteristics associated with end-use quality of bread and durum wheats. The analyses revealed that *T. tauschii* may be used for substantially increasing the number of high molecular weight glutenin (HMWG) subunits present in bread wheat (HMWG subunit composition is implicated in the definition of gluten strength in both bread wheat and durum wheat) (Payne et al. 1981; Pogna et al. 1990).

We have also examined variability for quality (grain hardness, protein content, and SDS-sedimentation) as well as the relationship between quality and HMWG and low molecular weight glutenin (LMWG) subunit composition (SDS-PAGE) in 137 accessions of *T. dicoccon*. Results confirm previous findings that *T. dicoccon* has more diverse genetic variability for alleles involved in the synthesis of gluten-type proteins than cultivated wheat. *T. dicoccon* should be considered a good potential source for improving gluten strength in bread and durum wheat.

In the past three years, the frequency of high quality CIMMYT bread wheats has increased dramatically. A modification of the crossing strategy, emphasizing high quality parents, was implemented in the early 1990s. Quality testing of advanced generation breeding materials was increased over the past few years. Now these two strategies have come to fruition. In the near future, about 75% of CIMMYT's new bread wheat germplasm will be competitive for quality standards in the marketplace.

Biotechnology and Wheat Improvement: An Example of Collaboration

By drawing on the power of biotechnology, CIMMYT seeks to make plant breeding more efficient and, in some cases, to improve wheat in ways that have eluded conventional breeding approaches. The comparative genetic mapping of cereal genomes has identified a vast amount of conserved linearity of gene order (Devos and Gale 1997). This observation is likely to accelerate the application of quantitative trait loci (QTL) in wheat, as well as aid in the identification of genes required for introgression from alien species. Given the low number of loci tagged at present in wheat, the problems related to developing a high-density map for wheat (Snape 1998), and the limited progress to identify QTL for yield in wheat, we believe that the impact from this linearity on wheat improvement will be significant.

An extremely positive development in CIMMYT's efforts to apply biotechnology to wheat improvement is participation as a core partner in the Cooperative Research Centre (CRC) for Molecular Plant Breeding, established and supported under the Australian government's Cooperative Research Centres Program. The CRC collaboration features two main projects. The first projects aims to identify molecular markers for resistance to leaf rust and yellow rust. In line with the rust resistance breeding strategy described previously, researchers from CIMMYT and Australia are looking for minor genes to create durable resistance. For CIMMYT's partners in the international wheat improvement system, the value of this project is clear. For Australia, this work will prove valuable in the event that rust resistance in its wheat varieties (largely based on major genes) breaks down, as has occurred on occasions in the past.

The second project in the CRC collaboration focuses on introducing, via transgenics, resistances to some fungal pathogens of wheat and then characterizing their effects. An important aspect of this work is to increase transformation efficiencies, which were low at the outset. Rates of transformation have been significantly increased (efficiency was 0.2-0.4% before; now it averages about 1% and may reach 5% in the near future), and researchers are proceeding with the other objectives.

By collaborating with the many institutes involved with the CRC that are leaders in molecular genetics in wheat, CIMMYT can tap into their expertise in ways that will greatly benefit many of our partners in the international wheat improvement system. Australia will also see positive results from the collaboration. According to the last annual report of the CRC for Molecular Plant Breeding, "CIMMYT's global field program provides CRC scientists with the opportunity to evaluate germplasm and populations in a wide range of environments. This makes it much easier for researchers to develop molecular approaches to the isolation of traits than if they were limited solely to Australia's agro-ecological environments" (CRC for Molecular Plant Breeding 1998).

Crop and Natural Resource Management Research

When combined with robust, highly productive crop varieties, it is not uncommon for improved management practices to raise farmers' yields twice and even three times. Strategic research on crop and natural resource management leads to improved farming practices and more sustainable maize and wheat production systems. Such research involves a complex iteration of field studies, crop and soil modeling, the use of geographic information systems, and remote sensing. At CIMMYT, agronomists are examining nutrient auditing and strategic fertilizer use; appropriate strategies for replenishing soil organic matter (such as green manures and crop residues); the development of suitable crop rotations; reduced tillage; and integrated pest and weed management. Some of these strategies are described in the sections that follow.

Improved Input Use Efficiency

Combining input efficiency with high yield potential in new cultivars will allow a farmer to benefit from these cultivars over a wide range of input levels. Selection for yield potential under medium to high levels of nitrogen has indirectly increased the efficiency of N uptake in CIMMYT wheats. Recently released CIMMYT bread wheat cultivars require less N to produce a unit of grain than cultivars released in previous decades (Ortiz-Monasterio et al. 1997). The increase in nitrogen use efficiency is shown in Figure 2. Under low N levels in the soil, N use efficiency increased mainly due to a higher N uptake efficiency—the ability of plants to absorb N from the soil—whereas under high N levels, the N utilization efficiency—the capacity of plants to convert absorbed N into grain yield—increased.

A study initiated in 1994 evaluated changes in soil nutrients and gas emission before and after fertilizer applications and compared alternative ways of applying nitrogen (Matson, Naylor, and Ortiz-Monasterio 1998). The experiment compared the common practice of Yaqui Valley farmers with alternatives that included reducing the amount of nitrogen applied and changing the timing of its application. The researchers found that with the farmers' practice, relatively high levels of nitrogen were lost into the

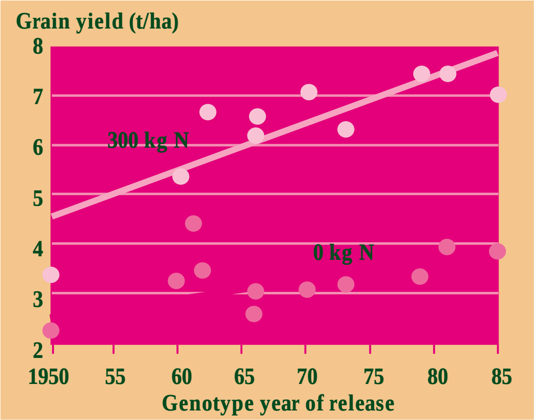

Figure 2. Grain yield of the historical series of bread wheats at Cd. Obregón, Mexico, at 0 and 300 kg/ha N application.

atmosphere when nitrogen came into contact with irrigation water, even before the wheat crop was in the ground. The best practice reduced the amount of nitrogen (from 250 to 180 kg / ha, one-third applied at planting and two-thirds six weeks later) and produced yields and grain quality similar to those obtained under the farmers' practice. The best alternative practice also saved US$ 55-76 / ha (equivalent to saving 12-17% in after-tax profits). The study shows that it is possible to reduce nitrogen gas emissions and fertilizer losses through appropriate agronomic practices and at the same time maintain yields.

Bed Planting Systems

A reduced tillage system developed by farmers and researchers in Mexico's Yaqui Valley is showing its potential there and in other irrigated wheat production environments. In this system, a crop is grown on raised beds that are divided by furrows for irrigation. No soil inversion tillage is used on the beds. Crop residues are chopped and left on the surface of the beds. The system has several advantages for farmers and the environment, including:

- Nitrogen can be applied when and where the wheat plants can use it most efficiently. Yields improve, and nitrogen losses into the environment are significantly reduced.
- Water conservation improves. As water for agriculture becomes more scarce in the years to come, water conservation practices will become more important for farmers. Researchers in South Asia and China report a 30% savings in water use from using bed planting and improved weed control.
- Weeds can be controlled by cultivating between the beds—reducing costs and the need for herbicide.
- Residues are returned to the soil without burning, which is beneficial to the environment.
- The beds can be used cycle after cycle. Farmers avoid the financial and environmental costs of making repeated passes with a conventional plow during land preparation.

Prototype machinery for this bed planting system has been designed and tested in Mexico and in Asia. The prototypes are modifications of standard agricultural equipment and are expected to be affordable for poor farmers. Mexican farmers reportedly save 30% on their production costs when they use the bed planting system. Some 10,000 farmers are thought to use the system in Mexico, and the number of farmers who are using bed planting is growing in South Asia and China as well. In fact, in parts of China some farmers find the technology so valuable that in the absence of equipment they form the beds by hand.

Farmer Participatory Research

Over the past few years, CIMMYT has significantly increased its investment in farmer participatory research for natural resource management (that is, in the development of productivity-enhancing, resource-conserving practices for maize and wheat systems, with beneficial impacts on soils, water, and agroecosystem diversity). Farmer participatory research is a tool for a purpose: the development of sustainable practices that improve resource quality while raising system productivity. CIMMYT is moving aggressively to mainstream the use of this tool for these important ends. For example, in irrigated areas in northern Mexico, CIMMYT has long collaborated with farmers in the development of the bed planting systems described earlier.

In Asia, CIMMYT works with the other members of the Rice-Wheat Consortium for the Indo-Gangetic Plains to foster farmer experimentation on reduced and zero tillage strategies for establishing wheat after rice. Farmer groups have assessed alternative tillage and sowing implements and wheat establishment strategies, and they have been encouraged to develop their own innovations and adaptations. Minimum tillage practices are spreading in Bangladesh, and farmers in the western part of the Indo-Gangetic Plains are beginning to use zero tillage. Farmers report earlier sowing, higher yields with lower levels of inputs, and improved possibilities for diversifying cropping patterns away from a continuous rice-wheat rotation—with numerous agroecological benefits.

In Bolivia, we are collaborating with farmer groups to develop zero tillage / mulch systems suitable for smallholders (2-5 ha) in the high inter-Andean valleys. These farmers produce one crop of wheat each year in monoculture or in rotation with potatoes, faba beans, peas, and / or barley. Research focuses on evaluation of straw cover to increase rainfall use efficiency. Results are extremely encouraging: crop residue retention generally increases yields and reduces risk, two important objectives for Bolivia's small-scale, subsistence farmers. Researchers also participate in a project to develop a small, animal-drawn, no-till seed drill for sowing cereals into surface residues, and results are very positive (CIMMYT 1999).

Information Management Tools for Sustainable Systems

Researchers have always believed in the value of sharing information more widely, but the limitations of information technology have not made this easy. CIMMYT now offers a widening array of information management tools to researchers in many disciplines.

For example, the International Wheat Information System (IWIS) is a relational database available on CD which gives each genotype a unique identifier and provides extensive pedigree and performance data. The Genetic Resources Information Package (GRIP), designed in conjunction with Australian partners, allows IWIS users to locate seed samples in wheat germplasm stocks in a number of collections around the world and provides an abbreviated version of the IWIS pedigrees. The International Crop Information System (ICIS) is a data management tool that builds on IWIS. It contains information on several crops in addition to wheat. The core of ICIS is a relational database structure that stores data on plant genetic resources, pedigrees, field and laboratory evaluations (including molecular information), and auxiliary data on locations, institutions, and people. Simple geographic information functions are being incorporated into ICIS, and a tool for exporting data to crop simulation models is also under development.

One challenge to sharing information more widely is to provide access to cutting-edge geographic information system (GIS) tools for non-GIS users, especially those in Africa. African researchers need spatially referenced data on climate, soils, infrastructure, crop distribution, and the natural resource base, in part to ascertain the extent to which their site-specific research may have relevance to larger areas. The Africa Country Almanacs contain such base data, along with the most commonly requested maps, plus search and viewing tools, on a single compact disc. Almanacs have been developed for 12 African countries,[5] some of which have requested follow-on demonstrations and training for their research staff. Now all researchers can have access to these powerful GIS tools, not just a few specialists in a central office.

The Spatial Characterization Tool (SCT) developed by CIMMYT and Texas A & M University goes a long way towards addressing the problem of "site specificity" in natural resources management research. Site researchers can now quickly perform "site similarity analysis," identifying areas with environments resembling that of their site. When applied to sites in Bolivia, this analysis uncovered environmentally similar areas within Bolivia; in neighboring countries (e.g., Chile, Brazil); within the Americas (e.g., Mexico); and even in other regions of the world (Ethiopia, Lesotho). Scientists in these diverse locations find that they have much to share about technology performance and the consequences of technical change for system productivity and sustainability.

These information management tools help encourage research integration, explore the prospective performance of new technologies, and overcome site specificity. However, like all information management tools, they need data. A final challenge is how to preserve, organize, and make available to researchers the rich array of data often generated by research, particularly in natural resource management research. CIMMYT is developing an answer to this set of challenges: the Sustainable Farming Systems Database (SFSD). Non-governmental organizations are using the SFSD prototype to organize information on the global experience with green manure cover crops. As the SFSD matures, its uses will be virtually infinite.

5 Including three important wheat producing nations: Ethiopia, Kenya, and Zimbabwe.

Conclusions

The strategies we have just outlined could make the difference between a sustainable future, with food and economic opportunity available for the majority, and a future of scarcity, with survival seriously compromised for most people. Successful, sustainable agriculture can help create the purchasing power and employment that will ensure food security and help eradicate poverty. We believe that the risks of ignoring agricultural development will be far higher than the risks of deciding to create a sustainable future for us all.

The world has faced a similar choice before, when a decision was made to sow the new semidwarf wheats in India in the hope that their higher yields would prevent a famine as great as the devastating Bengal famine of 1943. That decision transformed agriculture and the way that agricultural research was conducted. Today CIMMYT and its partners join forces in one of the world's most ambitious endeavors: we participate in a global wheat improvement system that continues to better the lives of millions of poor farmers and consumers in developing countries. The impact of that system is well documented (Byerlee and Moya 1993; Maredia and Byerlee 1999; CIMMYT 1999). In the most recent period, 1991-97, almost 90% of the spring bread wheat varieties released by national agricultural research systems had CIMMYT ancestry (Figure 3). Virtually all (98%) of the spring durum wheats released by national programs in 1991-97 had CIMMYT ancestry (Figure 4). Farmers now plant almost 80% of the developing world's spring bread wheat area to CIMMYT-related wheats (Figure 5).

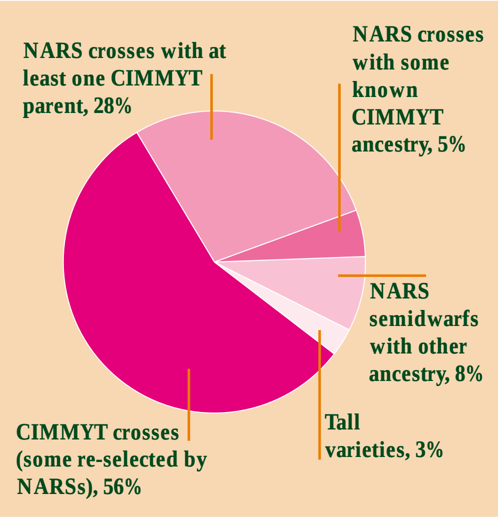

Figure 3. Ancestry of spring bread wheat varieties released by national programs, 1991-97.
Source: CIMMYT wheat impacts database.

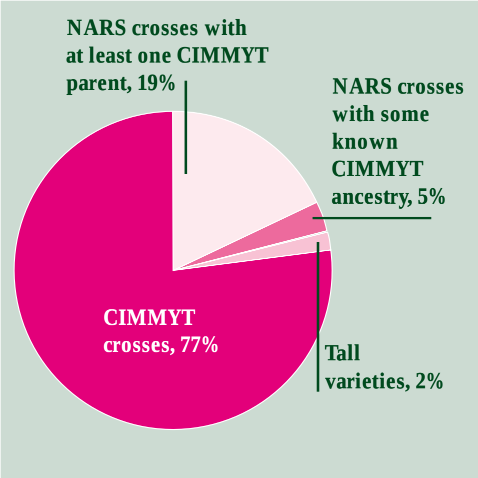

Figure 4. Ancestry of spring durum wheat varieties released by national programs, 1991-97.
Source: CIMMYT wheat impacts database.

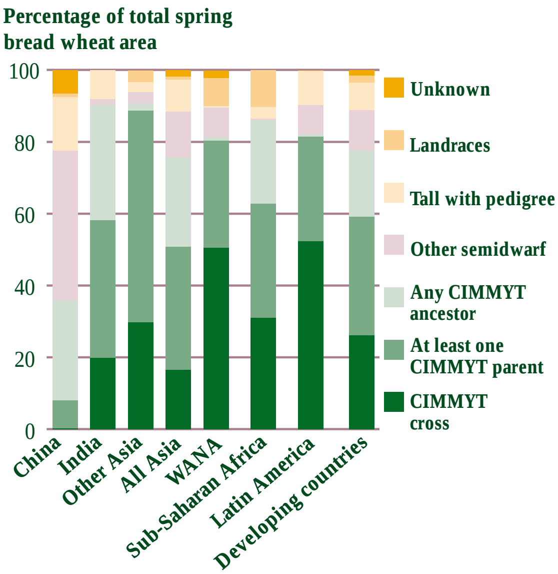

Figure 5. Area planted to spring bread wheat in developing countries, 1997.
Source: CIMMYT wheat impacts database.

A New Research Paradigm for New Research Impacts

These research impacts are reassuring, but much remains to be done. When our colleague Norman Borlaug accepted the Nobel Peace Prize for his achievements in bringing about the Green Revolution in wheat, he cautioned that the Green Revolution "has not transformed the world into Utopia. None are more keenly aware of its limitations than those who started it and fought for its success. . . . Above all, I cannot emphasize too strongly the fact that further progress depends on intelligent, integrated, and persistent effort" (CIMMYT 1970).

Borlaug's observation remains true. If we are to make progress toward sustainable food security, we must take his advice and change the way we plan, conduct, and communicate about research. We must blend very specialized research disciplines in teams of scientists seeking appropriate outcomes that have an immediate impact in farmers' fields. It is from these fields that food supplies must come for the foreseeable future. The farmer is the ultimate systems-oriented operator, juggling biological, economic, environmental, and social factors. In such circumstances, isolated interventions are of limited value at best; all too often, they make things worse.

These interventions will be based on a new, integrative research paradigm that focuses on the elements of the GxExMxP equation mentioned earlier: the best genotypes (G), in the right environments (E), under appropriate crop management (M), generating appropriate outcomes for people (P). Everyone who seeks to foster sustainable agriculture in developing countries should recognize the interdependence of these factors, because most organizations by themselves cannot contribute fully to each aspect of GxExMxP. Partnerships and consortia that assemble the best possible teams to execute the GxExMxP approach will underpin the timely and successful achievement of sustainable farming systems and future food security.

The Shape of Things to Come

Given these requirements, what will agricultural research look like in the new millenium? Every member of the international wheat improvement system—and the farmers and consumers who depend on it—will be affected by changes in international research in the years to come. Which forces are likely to shape the way that research is done—either by contributing to or detracting from the integrative research paradigm we have just described?

For decades, collaboration has been the mainspring of the international wheat improvement system. None of the achievements described in this paper could have been attained without it. Gains from conventional breeding will continue to be significant in the next two decades or more (Duvick 1996), but these are likely to come at a higher cost than in the past. Research managers and policy makers are increasingly concerned that the very open, collaborative networks that have sustained the wheat improvement system will become far more circumscribed in coming years.

Rasmussen (1996) has stated that nearly half of the progress made by breeders in the past can be attributed to germplasm exchange. In recent surveys of wheat breeders (Braun et al. 1998; Rejesus, van Ginkel, and Smale 1996), more than 80% of respondents expressed concern that plant variety protection (PVP) and plant or gene patents will restrict access to germplasm, with deleterious consequences for future breeding achievements. Regional and international nurseries are an efficient, low-cost means of gathering data from varied environments and exposing germplasm to diverse pathogen selection pressures, while providing access to germplasm and promoting germplasm exchanges. Breeders use cooperative nurseries extensively in their crossing programs, but the number of such nurseries has been greatly reduced during the past decade, partly because of increasing restrictions on germplasm exchange.

Recent developments in biotechnology for plant improvement have motivated much of the concern over PVP and other forms of intellectual property rights (IPR), as well as concern over germplasm exchange and developing nations' access to novel agricultural technologies. That debate promises to pale in comparison to another biotechnology-inspired debate, however, that has been prominent in the media.

The debate over the ethical uses of biotechnology has shifted to the agricultural sector. A furor over genetically modified plants (focusing on uncertainty over their potential effects on human health and the environment) has swept across Europe, where "the public's perception of risk far outweighs its view of the possible benefits" (*The Economist*, 19 June, 1999). Within development circles, some argue that it is too risky to use genetic engineering to solve poor people's problems because we may be unaware of future side effects. Others question whether it is ethical to withhold solutions to problems that cause millions of children to die from hunger and malnutrition. Clearly we must seek acceptable levels of biosafety before releasing products from modern science, but it is critical that the risks associated with the solutions be weighed against the ethics of not making every effort to solve food and nutrition problems.

These highly public—and highly charged—debates make it easy to lose sight of another trend in the research environment that is almost more worrying. For a host of reasons, many national agricultural research systems have become weaker over the past two decades rather than stronger. At the international level, public support for broad research initiatives, such as CIMMYT's improvement of wheat germplasm for the major environments in the developing world, has diminished as public research investments have increasingly focused on more narrowly targeted projects. Under these circumstances, can we reasonably expect the public sector to be an effective advocate on behalf of the poorest constituents of society? Will the declining resources commanded by the public sector interfere with germplasm testing and exchange even more than the trends described earlier? Given the vast resources commanded by private research organizations, what is the future role of the public sector in crop improvement research?

Despite these uncertainties in the research environment, our ultimate objective remains clear. We know that to ensure food security in the 21st century, the sustainable intensification of agriculture in farmers' fields is essential. With 200 people added each minute to our population, and with all of us, rich and poor alike, dependent on a shrinking agricultural resource base, sustainable intensification is the only practical and appropriate choice for the foreseeable future. The new millenium holds out incredible promise—superior technology, unprecedented access to information, economic growth—but if these serve only to widen the gap between the "haves" and "have-nots," between the North and South, then what will we have gained? Of the many issues surrounding the future of international agriculture, this is perhaps the most important. It is *the central issue* that motivates CIMMYT's research agenda, and it will remain at the forefront of all of our future efforts.

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